Laser Induced Fluorescence for Photogrammetric Measurement of Transparent or Reflective Aerospace Structures

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ABSTRACT

To support the requirement for non-contacting measurement of polymer membrane structures a new technique based on the principles of photogrammetry has been developed and is described here.

INTRODUCTION

In recent years the development of high-resolution, high-frame-rate video cameras has helped support the emergence of photogrammetry and videogrammetry as a popular measurement tool for industrial applications. One of the limiting aspects with this technology for some applications has been the need to physically attach targets to the structural points of interest. This problem has been addressed by the development of dot projection techniques using white-light projectors that provide a completely non-contacting targeting mechanism[1]. To support the further application of this technique for objects that exhibit transparent or reflective properties an innovative laser-induced fluorescence targeting technique has been developed by NASA Langley Research Center.

A new generation of ultra-lightweight and inflatable "gossamer" space structures such as those shown in Figure 1 have been defined in NASA's "*New Millennium Program*". [2] The proposed structures will be designed with materials that are very smooth, thin, and highly transparent and/or reflective, such as the

LaRC™-CP1 transparent polymer membranes developed at NASA Langley Research Center. As the development of this new type of space structure continues the focus is shifting from design to measurement and control.

Large Antenna **Large Solar Sails** **Large Telescope Arrays**

FIGURE 1- NEW MILLENNIUM PROGRAM TECHNOLOGIES

To support modal analysis and the structural validation of these lightweight space structures a photogrammetric based method for non-contact ranging and surface profiling for transparent, translucent, reflective, or dark membrane and solid structures is being developed at the NASA Langley Research Center (LaRC). Classic measurement techniques and tools such as accelerometers, strain gages, laser ranging and scanning devices and even classic photogrammetry find limited application in this new generation of space structures because of the material properties. Surface contours can be determined with standard photogrammetric techniques (i.e. processing digital images to extract 3D object coordinates) by manually attaching small targets to the membranes. However, these targets are time consuming to apply, offer incomplete (and unchangeable) coverage of the surface, and most importantly they can affect the static and dynamic properties of the membranes[3].

PHOTOGRAMMETRIC PRINCIPLES

The basic data for photogrammetric measurements are images. In general, an image is the result of a perspective projection of a three-dimensional (3-D) object to two dimensions (2-D). Consequently, two or more photographic images can be “reverse engineered” to derive the shape of the original object. This process is called “Photogrammetry”. The photogrammetric solution provides a quantitative relationship between 3-D position and the 2-D image plane data recorded by one or more cameras. While photogrammetry has its roots in the topographic mapping and surveying, the last two decades have seen close-range photogrammetric techniques developed to support various industrial and research applications. For example, in some areas of aeronautics aeroelastic measurements including model deformation and wing twist based on photogrammetric measurements have become part of the standard data set[4]. Originally, the techniques were developed for use with still-frame film cameras, but the rapid development of CCD technology has led to the successful migration from film to video technology.

The principles supporting photogrammetric measurements are based on the intersection of converging light rays from a point or “target” as imaged by multiple cameras. A minimum solution requires two converging views, multiple perspectives similar to that shown in Figure 2 adds statistical strength and reliability to the solution since the redundancy ensures bad measurements will be detected.

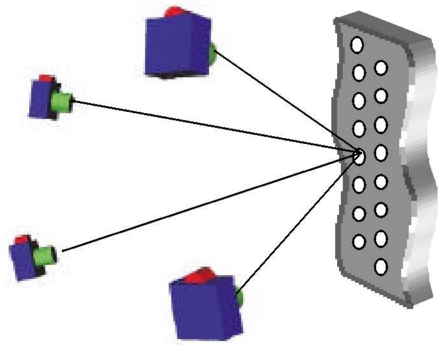


FIGURE 2– PHOTOGRAMMETRIC MEASUREMENT PRINCIPLE

Dot projection techniques provide a completely non-contacting spatially complete surface measurement technique suitable for near real-time applications. Projecting a white light dot pattern using a slide or computer projector has been successfully demonstrated at LaRC on many diffuse structures[5]. However, when this method is used with highly transparent or highly reflective materials, most of the projected light either passed directly though the membrane or was reflected in undesirable directions as depicted in Figure 3. Consequently, sufficiently high contrast images are difficult to obtain at the high frame rates needed to support dynamic measurement. A new method is presented here that can overcome the optical difficulties of transparent and reflective membranes, while maintaining minimal impact on the structural characteristics of the test articles.

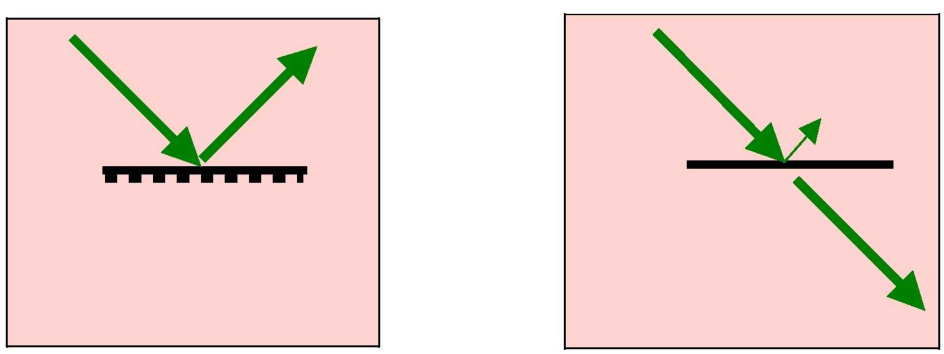


FIGURE 3 – LIGHT SCATTERING PROPERTIES – TRANSPARENT/REFLECTIVE MEMBRANE SURFACES

EXPERIMENTAL DESCRIPTION

Laser-induced fluorescence dot projection is a promising new technology for photogrammetry of transparent and reflective space structures. Very small concentrations of fluorescing dye have been successfully introduced into LaRC™-CP1 polymers during their manufacture, which upon excitation with a laser source fluoresces at a slightly longer wavelength. This fluorescence is emitted in all directions, thereby providing a significantly more predictable and repeatable dot pattern that can be viewed from any angle, enabling the capture of high contrast images. Image quality is also aided by spectral filtering and temporal gating to reduce the influence of stray laser and extraneous light.

Problems associated with laser dot projection techniques caused by speckle are also eliminated because the fluorescence is not coherent[6]. The optical properties associated with laser-induced fluorescence for both transparent and reflective surfaces are illustrated in Figure 4.

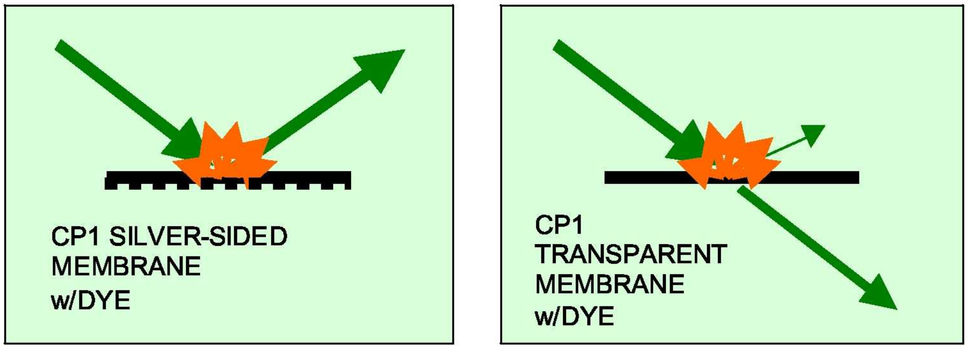


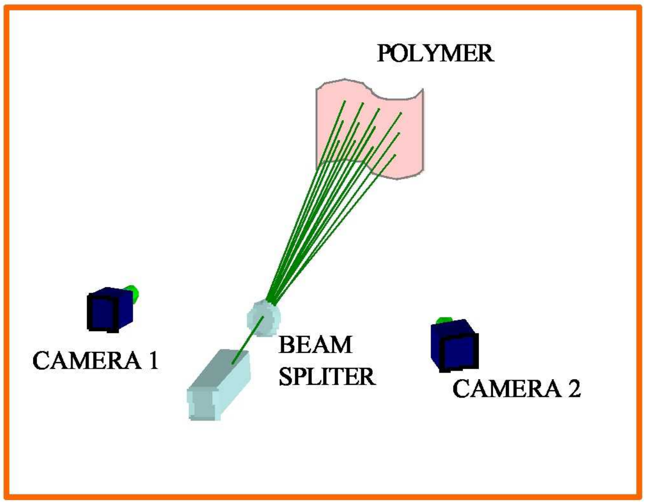
FIGURE 4 – FLUORESCENT LIGHT SCATTERING – DYE DOPPED MEMBRANE

An example of a small LaRC™-CP1 polymer manufactured by SRS Technologies Inc. (Huntsville, Ala.) with an added concentration of the fluorescing dye is shown in Figure 4; note the nearly transparent properties of the film. While the specifications for material thickness of membranes identified for use in inflatable space structures has not been defined, the long term goals as specified by the program indicate that material densities will need to be less than 5g/m^2 to support the diverse requirements of future space missions. With this goal in mind it was determined that the added concentrations of the dye to the polymer should be kept to the minimum necessary to support the measurement. As a starting point, samples with concentrations up to 0.01% (wt/wt) were developed for evaluation.

FIGURE 5 – LaRC™-CP1 SAMPLE POLYMER WITH DYE

SYSTEM CONFIGURATION

To demonstrate the laser induced fluorescence photogrammetric technique, measurements were performed on simple small-scale prototype polymers. The major hardware components required to demonstrate the technique are a low power laser, a diffractive pattern generating optical element, and a pre-calibrated high-resolution professional grade digital camera. Unlike laser scanners or trackers that are limited because of the use of a single beam, this technique splits the primary beam into the beam pattern necessary to cover the structure. The multiple beams strike the polymer creating an array of fluorescing dots or "targets". Since the fluorescence is at a longer wavelength than the laser excitation a long-pass optical filter is placed in front of the camera to reject the laser's frequency, thereby increasing the signal to noise ratio. High contrast images of the fluorescent targets are then acquired from a minimum of two perspectives to determine the spatial coordinates of the targets. The hardware configuration for this experiment is illustrated in Figure 6.



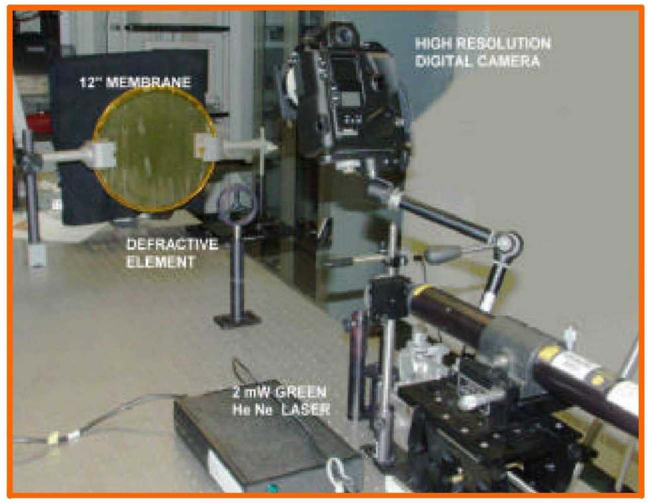


FIGURE 6 – HARDWARE CONFIGURATION FOR LASER INDUCED FLUORESCENCE

Photomodeler® an image processing software package from EOS Systems Inc. was used to perform the basic photogrammetric computations required to generate a surface contour for the tested polymers.

To better illustrate the effectiveness of the fluorescing technique two case studies were undertaken that because of the material properties would have been very difficult if not impossible to measure using standard photogrammetric targeting techniques.

CASE 1 TRANSPARENT MEMBRANE

The first case study involved a simple 12-inch diameter circular membrane stretched over a hoop to provide uniform tension, similar to that shown in Figure 5. The membrane had an average thickness of 0.001 inches. A low power, 2mW green Helium Neon (He-Ne) laser was used as a source. A diffractive optic was used to produce a 19x19 grid over the surface of the membrane. The camera, a professional grade six mega-pixel Kodak DCS 760 was configured with a Kodak #22 Wratten Gelatin filter to block all light below that wavelength. The camera was pre-calibrated to determine all camera parameters and lens distortions. The effectiveness of the filtering is a key aspect for obtaining images from multiple perspectives that would otherwise suffer from glints and reflections that over expose large regions of the membrane. The filter used in this experiment provides less than 0.5% transmittance for light below 550 nm, and 60% transmittance at the wavelengths corresponding to the emitted fluorescence.

To demonstrate the ability of the photogrammetric technique to resolve small surface distortions in the membrane the hoop was compressed in one direction to induce small wrinkles. Figure 6 shows the 12-inch hoop membrane and the fluorescent pattern created by the laser projection. The size, density and arrangement of the target pattern can be easily adjusted to fit any test article with the additional optics. The lower intensity dots visible around the edges of the 19x19 projected pattern are second and higher order diffractive patterns.

To complete the processing the target centroid is computed for each of the visible targets. Various commercial image-processing tools are available to compute target centroids with sub-pixel accuracy. The computed target information is then used to calculate the 3D spatial coordinates of the membrane. A shaded relief map created with the spatial coordinates is illustrated in Figure 7. The coordinate system was transformed to show all amplitude variations in the z-axis. The range of amplitudes as shown in Figure 8 is ±1.5mm.

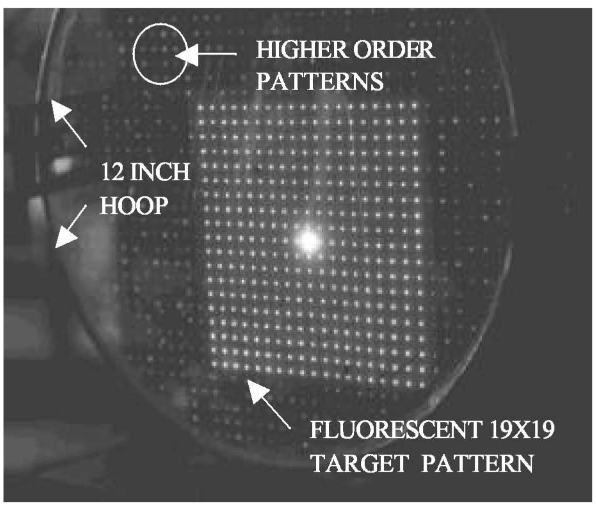


FIGURE 7. FLUORESCENT TARGET PATTERN ON TENSIONED TRANSPARENT MEMBRANE

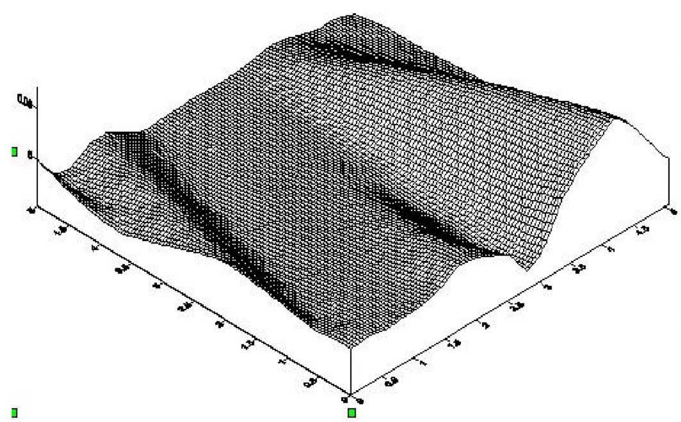


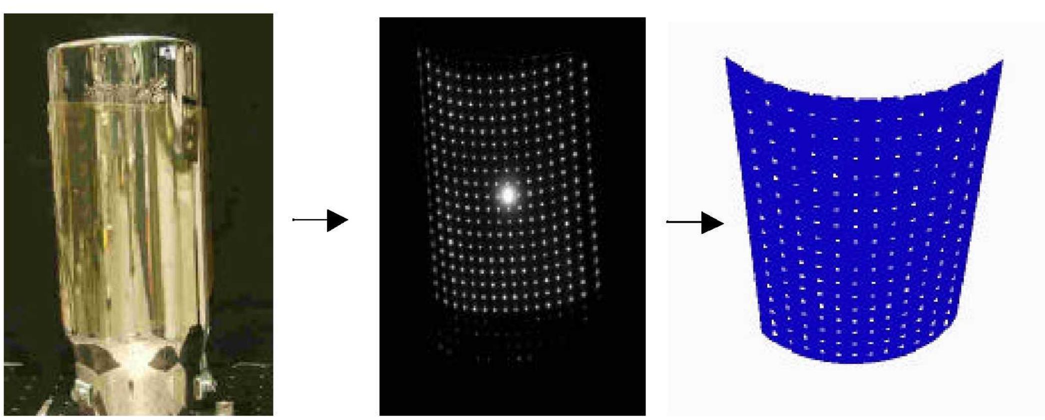
FIGURE 8. SHADED RELIEF MAP OVERLAID WITH WIREFRAME MODEL OF WRINKLES IN COMPRESSED MEMBRANE

CASE 2 REFLECTIVE MEMBRANE

This case study used a transparent dye doped membrane wrapped around a small 5½inch polished stainless steel cylinder. The intent was to simulate the effect of a polymer with a reflective coating that is shaped to a non-planar surface. This configuration best simulates the reflective properties expected of various structural components for inflatable antennas, concentrators and solar sails.

The measurement of the static shape of the cylinder is conducted with the same hardware described in the first case study. The exposure time required to achieve the minimum contrast necessary was 1 second. For this case the diffractive optic was again positioned to generate a 19x19 grid.

The stainless steel cylinder with the membrane attached is shown in Figure 9(a), the fluorescing target pattern created by the laser on the surface of the cylinder is shown in Figure 9(b), and a 3-D surface map of the cylinder using the derived coordinates of the targets is shown in Figure 9(c). The measurement was conducted with a series of photographs taken from four viewing angles. The reflective backdrop of the cylinder demonstrates an additional benefit for reflective coated polymers. The laser energy that passes through the polymer and that was not absorbed is reflected back through the membrane effectively double pumping the dye molecules. In addition, the fluorescence that is initially emitted in a direction away from the camera is reflected by the cylinder and is now visible from the front side. Collectively, these effects result in a 400% increase in the brightness of the fluorescent target. To validate the accuracy of the photogrammetric measurements the coordinate data for each of the 19 rows of targets, which formed a half-circle, was used to compute a radius. The average radius was 2.2486 inches, yielding a diameter of 4.4972. The average RMS for each row was 0.004 inches. A caliper was used to mechanically measure the diameter over the area covered by the projection. A series of 10 measurements were taken. The average diameter for the 10 readings was 4.501 inches.



(a) (b) (c)

FIGURE 9. MEMBRANE COVERED CYLINDER, FLUORESCING TARGETS, and 3D MODEL

To gain a better understanding of the advantages of the laser induced targets over the more conventional retro-reflective targets the cylinder was selectively covered with 1/8th inch retro-reflective targets and photographed at the same stations used for the measurement with the fluorescing targets. As expected the resulting images suffer from glints and source reflections that limit the completeness of the measurement. Two examples of the resulting image sequence are provided in Figure 10.

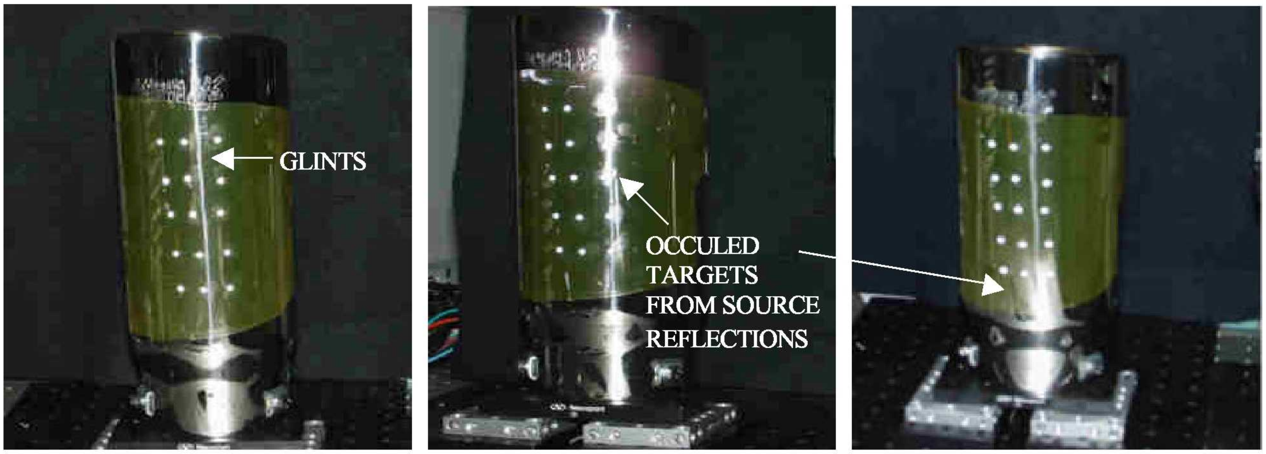


FIGURE 10. RETRO-REFLECTIVE TARGETS ON REFLECTIVE CYLINDER

In addition to being unaffected by glints and reflections the laser-induced targets have significant advantages of the retro targets, the most obvious being the target pattern density. The increased target density allows the measurement of surface imperfections that could potentially fall between the more sparsely targeted pattern typical with the use of retro targets. Even though in theory retro-reflective targets could be attached with the same density as a projected pattern this process would be very labor intensive, and would substantially alter the static and dynamic properties of the membrane. Furthermore, the projected dots can be magnified or concentrated to vary the resolution of the coverage, an example of a variation of the pattern size is shown in figure 11.

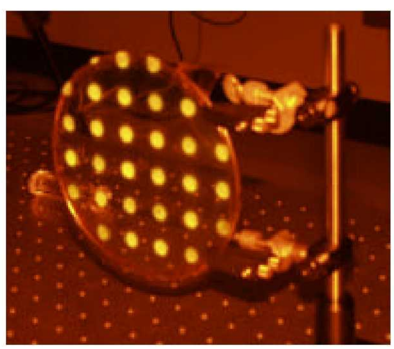


FIGURE 11. MAGNIFIED AND EXPANDED INDUCED FLUORESCENCE BEAM PATTERN

DYNAMIC MEASUREMENT (Future)

While the long exposure times (□ 1 sec.) typical for these case studies would not support dynamic measurement, lab test have demonstrated the linear relationship that exist between the laser power and the induced fluorescence. The data in Figure 12 illustrates this relationship over the power range of the

2 mW laser used for these experiments. It is therefore predicted that a high power pulsed laser would translate into shorter exposure times required for dynamic measurements. Further testing not described here has demonstrated the scalability of the process for dynamic measurements by configuring a pair of Pulnix scientific grade video cameras to operate asynchronously with an external trigger synchronizing their simultaneous exposure to the pulse of a 10mJ YAG laser.

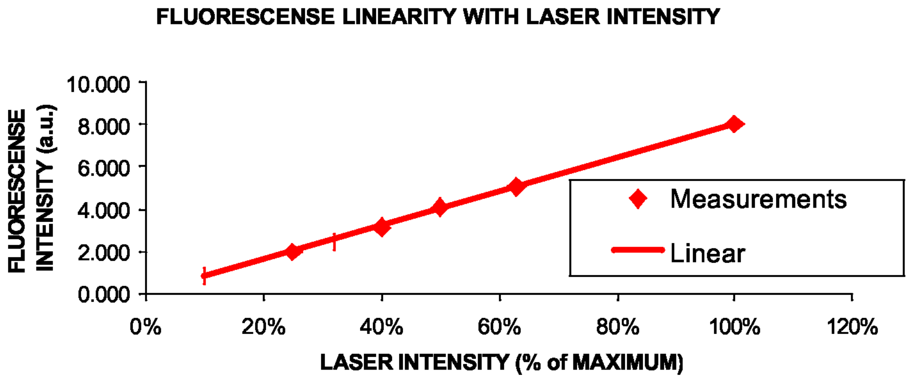


FIGURE 12. LASER INDUCED FLUORESCENCE POWER LINERITY TEST

CONCLUSIONS

Laser induced fluorescent targeting for inflatable membrane space structures holds the promise of providing spatially complete non-contacting measurements with immunity to the potential occlusions created by glints and reflections. The case studies highlight the advantages of fluorescent targeting when working with both transparent and reflective surfaces. By contrast, it has been demonstrated that results are unpredictable when conventional targeting techniques, such as retro-reflective targets are used on these same surfaces.

The non-contacting nature of the technique and the ability to quickly adjust the target pattern to the individual test article make this a viable technique for both ground validation and flight experiments for the new generation of inflatable space structures.

The future development of this technique using multiple scientific video grade cameras for near real time measurement will likely have a substantial influence on the dynamic measurement and control of large inflatable space structures.

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